1996

On the strategic potential of technological aid in international environmental relations

JK Stranlund

On the Strategic Potential of Technological Aid in International Environmental Relations

John K. Stranlund

Received January 3, 1996; revised version received June 13, 1996

Prior to noncooperative choices of abatement of a transboundary pollutant, a technologically advanced country considers making an unconditional transfer of abatement technology to its less-advanced rival. Even though technological aid is given unconditionally and abatement strategies are chosen noncooperatively, in a number of plausible circumstances, a transfer of a superior control technology will induce Pareto-superior pollution abatement.

Keywords: international environmental policy, technology transfer.

JEL Classifications: C71, D74, Q20.

1 Introduction

Many believe that the transfer of "clean technologies" to less-advanced countries will be an effective, even necessary, policy prescription to confront international environmental problems (French, 1992; Heaton et al., 1991; Levy et al., 1993; Pearce, 1991; von Moltke, 1992).[1] Guaranteeing easy access to new technologies is often justified as a cost-effective way to reduce international emissions of some pollutants. For example, concerning the policy debate about confronting global climate change, there appears to be significant potential for improving the efficiency of energy use in the developing world. Transferring energy-efficient technologies to less-advanced countries may be a relatively inexpensive way to reduce global emissions of greenhouse gases (De Canio and Lee, 1991; Coppel, 1994). Facilitating the transfer of clean technologies has also been made a concrete part of a number of interna-

1 "Clean technologies" generically refer to a wide range of devices, management techniques, and materials that are used to control emissions or produce goods and services with lower environmental impacts.

tional environmental agreements. For example, the 1989 "Basel Convention on Hazardous Wastes" obligates parties to provide technical assistance to less-developed parties. Under the 1990 "London Amendments to the Montreal Protocol on Substances that Deplete the Ozone Layer," industrialized parties to the Protocol are to make ozone-benign technologies (substitutes for chlorofluorocarbons and halons) available to developing countries on "fair and most favorable terms" (Benedick, 1991; Parsons, 1993).

Despite the consensus that technology transfer is likely to be an effective policy instrument in international environmental relations, the economic and game-theoretic literature on international environmental conflict resolution lacks a rigorous examination of its strategic potential.[2] Hence, in this paper we will consider whether a country can use technological aid to its strategic advantage in a two-country game of abatement of a transboundary pollutant.

We will restrict our attention to situations in which the countries do not expect to come to a binding agreement to control emissions of the pollutant, so the game is completely noncooperative. Furthermore, as is often assumed in the literature on international environmental problems, reducing emissions of the transboundary pollutant is modeled as a contribution to a pure public good (international environmental quality).[3] We shall consider a two-stage game. In the first stage of the game, the technologically advanced country may make an unconditional gift of a superior abatement technology to the other country. In the second stage, the countries noncooperatively choose their abatement strategies.[4] In this context, we will find that a number of plausible

---

2 Some examples of theoretical analyses of international environmental conflict and resolution include Barrett (1994), Black et al. (1993), Carraro and Siniscalco (1993), Hoel (1991), Mäler (1991), Sandler and Sargent (1995), and Welsch (1993). None of these papers consider the role of technology transfer.

3 The theory of private contributions to public goods is relevant here. A typical list of citations will include Bergstrom et al. (1986) and Cornes and Sandler (1986) among many others. Recent contributions include Varian (1994), Konrad (1994), and Buchholz and Konrad (1995). The assumption that abatement is a contribution to a pure public good is appropriate when considering problems like ozone depletion and global climate change which are generated by uniformly mixed pollutants. Hoel (1991), Welsch (1993), and Buchholz and Konrad (1994) assume a uniformly mixed pollutant. If the pollutant is not uniformly mixed the damage inflicted on a particular country depends on the source of emissions. For examples, see Maler (1991) who models European acid rain and Carraro and Siniscalco (1993).

4 As a model of a prior strategic investment to affect the outcome of a future noncooperative game, the paper is related to the industrial-organization

circumstances exist under which the advanced country will be able to use technological aid to its strategic advantage. Furthermore, when the advanced country transfers technology to the other, it induces Pareto-superior abatement choices. Thus, the results of this paper lend some theoretical support to the widespread belief that transferring superior abatement technologies can be an effective policy instrument in international environmental relations. However, because we also find that there are equally plausible situations in which a Pareto-superior outcome cannot be induced, policy recommendations about technological aid in a noncooperative setting should be considered cautiously.[5]

As a model of actions taken about abatement technology prior to abatement choices, this paper is closely related to a recent paper by Buchholz and Konrad (1994), in which they consider each country's adoption decision prior to abatement choices. They find that countries face a rather perverse incentive to adopt inferior technologies (in the sense that they involve higher unit abatement costs than other available technologies) so that they can precommit themselves to lower abatement in the future.[6] This paper differs from theirs because they do not consider technology transfer and we will not consider individual commitments to an abatement technology. Interestingly, the strategic aspects of the two approaches are quite similar. A technologically-advanced country has the incentive to transfer a superior technology for the same reason a country is motivated to choose an inferior technology for itself; both actions tend to shift the burden of reducing emissions onto others. However, as we shall find, the welfare and environmental consequences of the two types of actions are very different.

A relatively general version of the game is described in Sect. 2. This section provides a number of interesting results about the effects of transferring a superior technology on second-stage abatement choices

---

literature on strategic investments to forestall entry or expansion of a rival firm. (Typical references include Dixit, 1981, Fudenberg and Tirole, 1984, and Gilbert, 1989, among many others.)

5 Since this paper assumes that the advanced country is restricted to *giving* its rival a superior abatement technology, it does not consider the possibility of mutually advantageous trades in which the less-advanced country purchases a superior abatement technology. Allowing such trades should result in a larger set of Pareto-improving transfers.

6 They also find that a nation is motivated to adopt inferior abatement technologies prior to a cooperative agreement because doing so will improve its bargaining position. In a related paper, Copeland (1990) finds that, in the absence of international cooperation, countries may have a strategic incentive to degrade common property resources to influence the behavior of rival nations.

and a characterization of the subgame-perfect equilibrium. To provide a clearer picture of equilibrium transfers, an example is presented in Sect. 3. In this section we will see that the policy problem of identifying an optimal transfer may be quite difficult. Section 4 concludes.

2 The Game

The players of the game are two countries, which we shall call the North and the South. (Imagine benevolent governments acting on behalf of their citizens.) Suppose throughout that the North possesses superior abatement technologies. In the first stage of the game, it may *give* a superior abatement technology to the South to influence the outcome of the second-stage abatement game. The transfer of a superior technology is completely unconditional – the South does not pay a price for a superior technology, nor is it obligated to a particular abatement choice in the second stage of the game. A subgame-perfect equilibrium of this game consists of a technology transfer in the first stage, and noncooperative abatement choices in the second stage, conditional on the first-stage transfer.

2.1 Technology Transfer

Let the total cost of x_{N} units of abatement by the North be the monotonically increasing and strictly convex function $c_{\mathrm{N}}(x_{\mathrm{N}})$. The South's abatement cost function is assumed to be $c_{\mathrm{S}}(x_{\mathrm{S}}, t)$ which is increasing at an increasing rate in its abatement x_{S}. The variable t is taken from a continuous, nonnegative index of technologies defined on the closed interval $[0, t^0]$. The index orders the technologies according to their effectiveness in reducing the South's abatement cost so that $c_{\mathrm{S}}(x_{\mathrm{S}}, t)$ is decreasing in t. We will also assume that the South's marginal abatement cost is decreasing in t. Therefore, $\partial c_{\mathrm{S}}/\partial t < 0$ and $\partial^2 c_{\mathrm{S}}/\partial x_{\mathrm{S}} \partial t < 0$. We will say that t' is superior to (or more effective than) t'' if $t' > t''$.

Let $t = 0$ denote the technology that the South possesses at the beginning of the game, and let t^0 denote the best technology that the North possesses. In addition, the North possesses, or can develop at some cost, technologies that are inferior to t^0, but superior to technology 0. The open interval $(0, t^0)$ contains these technologies, each of which the North may choose to give to the South.

2.2 Second-stage Abatement

The welfare of country i is given by a utility function $u_i(x_{\mathrm{N}} + x_{\mathrm{S}}, y_i)$, which we shall assume is increasing at a decreasing rate in total abatement and increasing at a nonincreasing rate in private consumption. We shall also assume that consumption of environmental quality and the private good are weakly complementary. That is, $\partial^2 u_i / \partial X \partial y_i \geq 0$, where $X = x_{\mathrm{N}} + x_{\mathrm{S}}$. These assumptions along with those concerning abatement costs are sufficient to guarantee the results of this section.[7]

Let the price of private consumption be unity and let country i's exogenously given national income be m_i. Thus, the North's budget constraint is $m_{\mathrm{N}} = y_{\mathrm{N}} + c_{\mathrm{N}}(x_{\mathrm{N}})$ and the South's is $m_{\mathrm{S}} = y_{\mathrm{S}} + c_{\mathrm{S}}(x_{\mathrm{S}}, t)$. A subgame-perfect equilibrium of this game requires that second-stage abatement choices form a Nash noncooperative equilibrium that is conditional on the first-stage technology transfer. Given a technology that the South actually implements, a second-stage equilibrium is a pair of abatement choices $[x^*_{\mathrm{N}}(t), x^*_{\mathrm{S}}(t)]$ which solve the following optimization problems simultaneously:

$$\begin{aligned} &\max_{x_{\mathrm{N}}} u_{\mathrm{N}}(x_{\mathrm{N}} + x_{\mathrm{S}}, m_{\mathrm{N}} - c_{\mathrm{N}}(x_{\mathrm{N}})) \ , \\ &\max_{x_{\mathrm{S}}} u_{\mathrm{S}}(x_{\mathrm{N}} + x_{\mathrm{S}}, m_{\mathrm{S}} - c_{\mathrm{S}}(x_{\mathrm{S}}, t)) \ . \end{aligned} \tag{1}$$

To analyze how the first-stage technology transfer affects second-stage abatement choices, let us consider the Nash best-response functions of the countries and focus on unique, interior second-stage equilibria. For the North the best-response function is $x_{\mathrm{N}} = \phi_{\mathrm{N}}(x_{\mathrm{S}})$ which is implicitly defined by the first-order condition $\partial u_{\mathrm{N}}/\partial x_{\mathrm{N}} = \partial u_{\mathrm{N}}/\partial X - (\partial u_{\mathrm{N}}/\partial y_{\mathrm{N}})c'_{\mathrm{N}} = 0$. The best-response function of the South is $x_{\mathrm{S}} = \phi_{\mathrm{S}}(x_{\mathrm{N}}, t)$ which is implicitly defined by $\partial u_{\mathrm{S}}/\partial x_{\mathrm{S}} = \partial u_{\mathrm{S}}/\partial X - (\partial u_{\mathrm{S}}/\partial y_{\mathrm{S}})(\partial c_{\mathrm{S}}/\partial x_{\mathrm{S}}) = 0$.[8] The best-response functions have the following characteristics:

$$\frac{\mathrm{d}\phi_{\mathrm{N}}(x_{\mathrm{S}})}{\mathrm{d}x_{\mathrm{S}}} \in (-1, 0), \quad \frac{\partial \phi_{\mathrm{S}}(x_{\mathrm{N}}, t)}{\partial x_{\mathrm{N}}} \in (-1, 0), \quad \text{and} \quad \frac{\partial \phi_{\mathrm{S}}(x_{\mathrm{N}}, t)}{\partial t} > 0 \ . \tag{2}$$

7 With $\partial^2 u_i / \partial X \partial y_i > 0$, it can be shown that environmental quality and private consumption are strictly normal goods. That is, holding abatement of the other nation constant, an increase in income will be allocated to increased abatement and increased consumption of the private good.

8 Of course, the best-response functions also depend on income levels, but these are ignored because they are not needed for our purposes.

(These relations are derived in Appendix 1.) The first two relations indicate that a unit increase in a country's abatement motivates its rival to reduce its abatement, but by less than a unit. The third relation indicates that, given an abatement choice by the North, the transfer of a superior technology motivates the South to increase its abatement.

If the second-stage equilibrium is unique, the North's equilibrium abatement must satisfy $x_N^*(t) \equiv \phi_N[\phi_S(x_N^*(t), t)]$. Differentiating this identity and rearranging yields

$$\frac{\mathrm{d}x_N^*(t)}{\mathrm{d}t} = \left[\frac{\mathrm{d}\phi_N}{\mathrm{d}x_S}\frac{\partial\phi_S}{\partial t}\right]\left[1 - \frac{\mathrm{d}\phi_N}{\mathrm{d}x_S}\frac{\partial\phi_S}{\partial x_N}\right]^{-1} < 0 . \tag{3}$$

The sign of this marginal effect follows from the characteristics of the best-response functions given by (2). In addition, the South's equilibrium abatement must satisfy $x_S^*(t) \equiv \phi_S(x_N^*(t), t)$. Differentiating this identity yields

$$\frac{\mathrm{d}x_S^*(t)}{\mathrm{d}t} = \frac{\partial\phi_S}{\partial x_N}\frac{\mathrm{d}x_N^*}{\mathrm{d}t} + \frac{\partial\phi_S}{\partial t} > 0 . \tag{4}$$

Lastly, one can use (3) and (4) to obtain the marginal relationship between total abatement and the first-stage transfer:

$$\frac{\mathrm{d}[x_N^*(t) + x_S^*(t)]}{\mathrm{d}t} = \frac{\partial\phi_S}{\partial t}\left[1 + \frac{\mathrm{d}\phi_N}{\mathrm{d}x_S}\right]\left[1 - \frac{\mathrm{d}\phi_N}{\mathrm{d}x_S}\frac{\partial\phi_S}{\partial x_N}\right]^{-1} > 0 . \tag{5}$$

Taken together, (3), (4), and (5) give us the equilibrium consequences of transferring a more effective abatement technology. Since a superior technology lowers the abatement cost (total and marginal) of the South, it is willing to take on a larger abatement burden. In response, the North reduces its abatement, but the overall effect is that total abatement increases. (The effects of transferring a more effective technology $t' > t$ are illustrated in Fig. 1.) These are essentially the strategic aspects of technological aid when two governments face a bilateral pollution problem in a noncooperative fashion. By investing in the abatement capability of another, a technologically advanced country can shift a portion of the burden of controlling emissions away from itself. Furthermore, such an investment leads to better environmental quality in both nations.[9]

9 Note that these results do not depend on the relative preferences for environmental quality in the North and South, nor do they depend on their

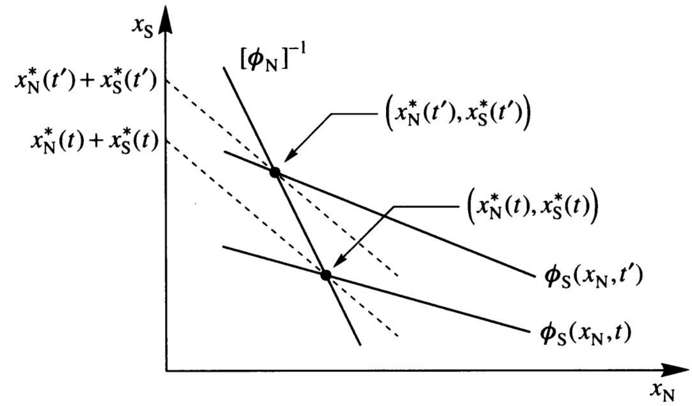

Fig. 1: The effects of transferring a more effective abatement technology on equilibrium abatement choices in the second stage

It is instructive to compare these results to those of Buchholz and Konrad (1994). They found that countries are motivated to adopt inferior abatement technologies to shift the burden of providing pollution control onto others. Adoption of a technology with higher unit abatement cost precommits a country to lower abatement in the future. (They assume constant marginal abatement costs.) In equilibrium, others respond with higher abatement. The essential aspect that drives the burden-shift is that the relative unit-abatement costs change. Adoption of an inferior technology implies that others have relatively lower unit-control costs, and hence, in equilibrium, they end up taking on a relatively larger abatement burden. A similar thing happens when one country provides another with a superior abatement technology; the donor nation's marginal control costs increase relative to the other's. In equilibrium, this induces a shift of the abatement burden onto the less-advanced nation. Though the burden-shifting characteristic of the two actions are the same, the environmental and welfare consequences are very different. Buchholz and Konrad find that environmental quality is unambiguously worse when nations strategically adopt inferior

relative control costs. In particular, the results do not require the North to have stronger demand for environmental quality or lower abatement costs. However, whether or not the focus on interior choices is justified will depend on relative preferences and costs. For example, if the North has significantly stronger preferences for environmental quality and significantly lower control costs, its choice of abatement may completely "crowd out" the South's incentive to control its own emissions.

control technologies, while we find that environmental quality is unambiguously better when a superior abatement technology is given to a less-advanced nation. Not surprisingly, they also find that strategic technology adoption has adverse welfare consequence. In contrast, we will be able to characterize situations in which technological aid induces Pareto-superior outcomes.

Since the underlying motivation for the North is to increase its control costs relative to the South's, it seems likely that the incentive to adopt an inferior control technology that Buchholz and Konrad identify will exist in spite of the North's motivation to transfer a superior technology to the South. That is, the North may find it optimal to simultaneously transfer a superior technology to the South and adopt an inferior technology for itself. In this paper we will ignore the latter incentive except to note that the transfer of superior technologies may enjoy broader political support than the adoption of an inferior technology. Thus, even though it may be rational for a country to adopt an inferior technology, it may not be politically feasible. Regardless, a more complete model of strategic technological choice in international environmental relations would allow for both actions.

In another related paper, Marjit (1990) finds conditions under which a technologically advanced firm can *sell* a superior production technology to its less-advanced Cournot rival. With linear demand and constant marginal production costs, it is straightforward to show that the strategic effects of a technology transfer are similar to those in the public-goods context; namely, output of the advanced firm decreases, output of its rival increases, and total industry output increases. However, in the duopoly situation, the transfer of a superior production technology without compensation would lead to lower profit for the advanced firm and higher profit for the less-advanced firm. Clearly, a superior production technology will never be freely given. If a transfer is to take place the less-advanced firm's gain in production profit must be large enough so that it is able to compensate the advanced firm for its loss of profit. In contrast, in the public-goods context the welfare of the North (excluding the costs of the transfer) must increase because environmental quality improves and it is able to reduce its emissions control. Hence, if the transfer cost is low enough, the North will always have an incentive to transfer a superior control technology without compensation from the South.

However, the South is not necessarily better off with a superior technology. Consider the South's equilibrium welfare $u_S^*(t) = u_S(x_N^*(t) + x_S^*(t), m_S - c_S(x_S^*(t), t))$. To see why the South may be worse off with a marginally superior technology, differentiate $u_S^*(t)$ and use the first-order condition $\partial u_S/\partial x_S = \partial u_S/\partial X - (\partial u_S/\partial y_S)(\partial c_S/\partial x_S) = 0$ to obtain

$$\frac{du_S^*(t)}{dt} = \frac{\partial u_S}{\partial X}\frac{dx_N^*}{dt} - \frac{\partial u_S}{\partial y_S}\frac{\partial c_S}{\partial t}\,.$$

Note that $du_S^*(t)/dt$ has the same sign as

$$\frac{\partial u_S/\partial X}{\partial u_S/\partial y_S}\frac{dx_N^*}{dt} - \frac{\partial c_S}{\partial t}\,. \tag{6}$$

Equation (6) shows that the South experiences a cost and a benefit from the transfer and adoption of a superior control technology. Recall that the transfer of a superior technology allows the North to reduce its emissions control. The first term in Eq. (6) is the value that the South places on the North's reduced emissions control. The second term is the reduction in the South's abatement costs due to adoption of the superior technology at its equilibrium abatement choice. Thus, if adopting a superior technology induces a relatively small reduction in the South's abatement costs, but a relatively large reduction in the North's equilibrium abatement which the South places a high value on, it may be worse off with a superior technology.

We shall give the South the ability to refuse a superior technology if its welfare is not improved. Let us assume for simplicity that if the South is offered a superior technology $t > 0$, it either adopts t or stays with its own technology 0. This assumption implies that receipt of some technology t does not make other technologies available to the South that are inferior to t, but superior to technology 0. Given some transfer t, denote the adoption strategy of the South as $i(t)$ and note that

$$i(t) = \begin{cases} 0 & \text{if } u_S^*(t) \le u_S^*(0), \\ t & \text{if } u_S^*(t) > u_S^*(0). \end{cases}$$

Clearly, this strategy does not involve any noncredible threats. Therefore, the North must account for this adoption strategy when it chooses a technology to transfer.

2.3 First-stage Technology Transfer

The North chooses a technology transfer in the first stage of the game by looking forward to the second-stage outcome. Transferring a technology has a cost which may include the costs of providing technical assistance for the installation and maintenance of a new abatement technology; expenditures to find and develop new technologies, or to modify existing technologies to make them appropriate for use in the South, and perhaps receipts that are foregone because a superior technology is simply given away. In this paper we assume that the North bears all the transfer costs, though one can easily imagine an agreement between the nations to share these costs. Allowing for such an agreement would result in a larger set of Pareto-improving transfers.

Suppose that the cost of transferring a technology t is given by $w(t)$ which is increasing at a nondecreasing rate. Since a transfer is costly, the North will only transfer technologies that the South will adopt, and thus, the North's transfer choice must satisfy $t = i(t)$. With this constraint in mind, the optimal transfer is determined by

$$\begin{aligned}&\max_t u_N\big(x_N^*(t) + x_S^*(t), m_N - w(t) - c_N(x_N^*(t))\big)\\&\text{s.t.}\quad t \in [0, t^0],\ t = i(t)\ .\end{aligned} \tag{7}$$

A first-stage transfer t^* that is a solution to (7) and the second-stage abatement pair $[x_N^*(t^*), x_S^*(t^*)]$ form a subgame-perfect equilibrium for the entire game.

Note that if the solution to (7) is such that $t^* > 0$, it must be a Pareto-improvement on the no-transfer case. Clearly, if $t^* > 0$ is a solution to (6), the North must be better off than in the no-transfer case. Also, since a solution $t^* > 0$ must satisfy the South's adoption requirement, it must also be better off than in the no-transfer case.

We conclude: If the North finds it optimal to transfer a superior technology to the South, doing so will induce Pareto-superior pollution control.[10]

Observe that this result is due to the structure of the game, not to any particular assumption about preferences or abatement costs.

3 Subgame-perfect Technological Aid: an Example

Unfortunately, at the level of generality assumed in the last section, a fuller characterization of possible subgame-perfect transfers is not possible. In this section we shall examine an example in which quadratic forms with nice curvature properties are adopted to uniquely identify equilibrium transfers. The example is used to illustrate an aspect of

10 Of course, because abatement strategies are chosen noncooperatively, the transfer of a superior technology cannot induce fully efficient pollution control.

technological aid that may be a significant consideration for policymakers in advanced countries. Namely, even though the utility and cost functions may be simple and well-behaved, the objective function for the North in the first stage of the game can easily be quite complex with boundary maxima and/or multiple local maxima. Thus, to actually identify a globally optimal transfer, policymakers in advanced countries may face the difficult task of estimating transfer costs and the benefits of pollution control; including, of course, the strategic interdependence of control policies, over the *entire* range of possible transfers.[11]

Assume that the utility functions are the following:

$$u_{\mathrm{N}}(x_{\mathrm{N}}, x_{\mathrm{S}}, y_{\mathrm{N}}) = \beta_{\mathrm{N}}(x_{\mathrm{N}} + x_{\mathrm{S}}) - \tfrac{1}{2}(x_{\mathrm{N}} + x_{\mathrm{S}})^2 + y_{\mathrm{N}} \ ,$$

and

$$u_{\mathrm{S}}(x_{\mathrm{N}}, x_{\mathrm{S}}, y_{\mathrm{S}}) = \beta_{\mathrm{S}}(x_{\mathrm{N}} + x_{\mathrm{S}}) - \frac{\eta}{2}(x_{\mathrm{N}} + x_{\mathrm{S}})^2 + y_{\mathrm{S}} \ ,$$

where β_{N}, β_{S}, and η are positive constants. Note that these utility functions are quasi-linear and strictly concave in pollution control. It seems likely that the country with superior abatement technologies generally has a stronger preference for environmental quality, so the analysis assumes that the North's demand for environmental quality is at least as strong as the South's. To capture this, we will assume that $\beta_{\mathrm{N}} \geq \beta_{\mathrm{S}}$ and $\eta \geq 1$. Under these assumptions, the marginal benefit to the South of total abatement does not lie above that of the North, and is at least as steep.

Suppose that the North's abatement-cost function is $c(x_N) = \frac{1}{2}x_{\mathrm{N}}^2$ and let the South's abatement-cost function be $c_{\mathrm{S}}(x_{\mathrm{S}}, t) = [(a-\pi t)/2]\cdot x_{\mathrm{S}}^2$, where $a > 1$ and π is a positive constant. Suppose that the range of $(a-\pi t)$ is the closed interval $[1, a]$. Then, t is defined on $[0, (a-1)/\pi]$. Note that if the North transfers its best technology $t^0 = (a-1)/\pi$, the abatement-cost functions of the two countries will be identical, otherwise the South's abatement cost lies above the North's.

Let us assume throughout that national incomes are sufficient to guarantee that the game admits equilibria in which private consumption by both countries is strictly positive. This assumption and quasi-linearity of the utility functions lets us ignore national incomes since they will have no bearing on optimal choices. Then, the counterparts

---

11 This problem is related to the well-known policy problem of *non-convexities* that arise in externality-control problems. See Baumol and Oates (1988) for an introduction, and Helfand and Rubin (1994) for a recent contribution.

of the optimization problems given by (1) are,

$$\max_{x_N} u_N(x_N, x_S) = \beta_N(x_N + x_S) - \tfrac{1}{2}(x_N + x_S)^2 - \tfrac{1}{2}x_N^2 ,$$

and (8)

$$\max_{x_S} u_S(x_N, x_S) = \beta_S(x_N + x_S) - \frac{\eta}{2}(x_N + x_S)^2 - \frac{a - \pi t}{2}x_S^2 .$$

Note that the objectives are strictly concave in individual abatement. Given some transfer from the first stage that the South adopts, and assuming an interior second-stage equilibrium, the equilibrium abatement choices are

$$x_N^*(t) = \frac{\beta_N(\eta + (a - \pi t)) - \beta_S}{\eta + 2(a - \pi t)} \quad \text{and} \quad x_S^*(t) = \frac{2\beta_S - \eta\beta_N}{\eta + 2(a - \pi t)} . \tag{9}$$[12]

(All the derivations of this section are given in Appendix 2.) We will focus on interior equilibrium abatement, which is guaranteed for all $t \in [0, (a-1)/\pi]$ if and only if $(2/\eta)\beta_S > \beta_N > (1/2)\beta_S$.

The payoff function for the South given some technology that it adopts is

$$u_S^*(t) = \beta_S[x_N^*(t) + x_S^*(t)] - \frac{\eta}{2}[x_N^*(t) + x_S^*(t)]^2 - \frac{a - \pi t}{2}x_S^*(t)^2 . \tag{10}$$

It is shown in Appendix 2 that $u_S^*(t)$ is strictly increasing in more effective technologies. Thus, for this example, if the South's equilibrium abatement choice is expected to be positive, it will adopt any superior abatement technology that the North chooses to transfer.[13]

To this point we have a very well-behaved system. The second-stage equilibrium choices of pollution control are unique, and, assuming as we do that they are interior choices, the South will adopt any superior

12 Note that the North's equilibrium abatement is decreasing in t, while the South's equilibrium abatement is increasing in t. Furthermore, it is easy to show that total abatement is increasing in t. These confirm our results from Sect. 2 that transferring a superior technology in the first stage allows the North to shift a portion of the burden of abatement onto the South and induces greater total abatement.

13 Even though the South's adoption strategy does not bind the North's choice of aid in this example, recall that this result cannot be generated in more general versions of the game.

technology the North chooses to transfer. The only thing left is for the North to choose a transfer $t \in [0, t^0]$ that maximizes $u_N^*(t) - w(t)$, where

$$u_N^*(t) = \beta_N[x_N^*(t) + x_S^*(t)] - \tfrac{1}{2}[x_N^*(t) + x_S^*(t)]^2 - \tfrac{1}{2}x_N^*(t)^2 \ . \quad (11)$$

As expected, $u_N^*(t)$ is strictly increasing in more effective technologies. However, assuming as we have been that the North's demand for environmental quality is at least as strong as the South's, $u_N^*(t)$ and $du_N^*(t)/dt$ are both strictly *convex* for all $t \in [0, (a-1)/\pi]$. (This result is also derived in Appendix 2.) Then, since $w(t)$ is convex (perhaps weakly), the North's objective in the first stage of the game, $u_N^*(t) - w(t)$, will likely lack the concavity property necessary for easy identification of an optimal transfer.[14]

Now, let us identify the possible subgame-perfect transfers for this example. To simplify matters, let us assume that the cost of transferring superior control technologies $w(t)$ is increasing at a linearly increasing rate, and that there are no fixed costs associated with transferring technology. (Of course, the presence of fixed costs can be another source of multiple local maxima.) Then, there are five cases to consider. The first three are illustrated in Fig. 2, which assumes that $du_N^*(0)/dt > w'(0)$. In case A, the marginal transfer cost function $w'_A(t)$ cuts $du_N^*(t)/dt$ once from below. In this case, the subgame-perfect transfer is t^3, a relatively modest investment in the South's abatement technology. In case B, the marginal transfer cost function $w'_B(t)$ cuts $du_N^*(t)/dt$ twice, once from below and once from above. In this case, there are two locally optimal transfers, t^2 and t^0. (Note that t^1 identifies a local minimum.) In case C, the marginal transfer cost function $w'_C(t)$ lies everywhere below $du_N^*(t)/dt$, so the subgame-perfect transfer is the best abatement technology t^0.

Cases B and C illustrate two important considerations for policymakers in the North. First, because of the strict convexity of $u_N^*(t)$, there are plausible circumstances under which it is optimal for the North to provide its best control technology so that the countries' abatement capabilities are equalized. Second, case B illustrates the possibility of two locally optimal transfers, one of which is the transfer of the best technology. The presence of multiple local maxima is problematic because if the North considers only incremental investments from the status quo

14 This is true even though the underlying utility and abatement-cost functions are quite simple. With more complicated utility and cost functions, we should expect that the North's first-stage objective will be even more complex.

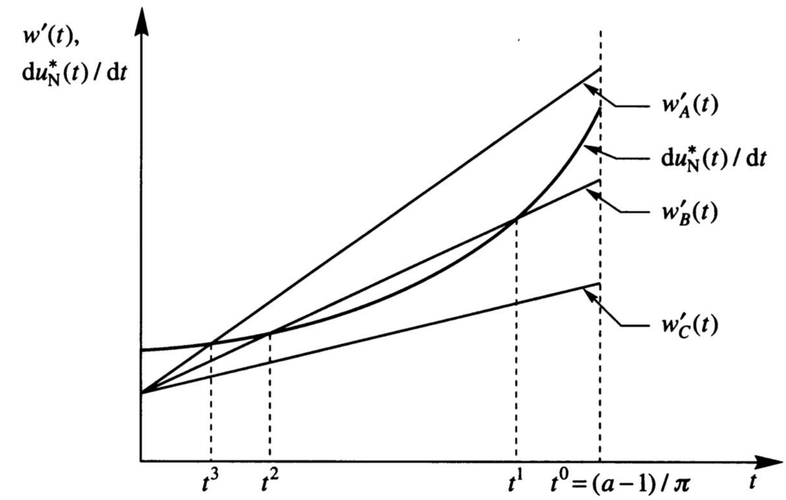

Fig. 2: Possible subgame perfect transfers when the North's preference for environmental quality is at least as strong as the South's, and $du_N^*(0)/dt > w'(0)$

($t = 0$), a simple "marginal benefit equal to marginal cost" rule will lead it to settle on a moderate transfer like t^2 when a more radical investment like transferring its best technology may be the global optimum. The fact that the optimal transfer may be the best technology and the possibility of multiple local optima seem to imply that policymakers in the North need to be able to estimate the net benefits of pollution control and transfer costs over the entire range of potential transfers. Clearly, this will be a difficult task.

The two remaining cases are illustrated in Fig. 3, which assumes $du_N^*(0)/dt < w'(0)$.[15] In case D, the marginal transfer cost function $w'_D(t)$ lies everywhere above $du_N^*(t)/dt$. Here, any improvement in the South's abatement technology is too costly, so in the subgame-perfect equilibrium, no transfer takes place. In case E, the marginal transfer cost function $w'_E(t)$ cuts $du_N^*(t)/dt$ once from above, so the subgame-perfect equilibrium consists of the transfer of the best abatement technology or nothing at all. Case E is interesting because modest transfers are too costly, but equalizing the abatement capabilities of the two nations may be a Pareto-improvement. Again, a search only over incremental improvements in the South's abatement capability may lead policymakers

15 These cases also apply when $du_N^*(0)/dt = w'(0)$.

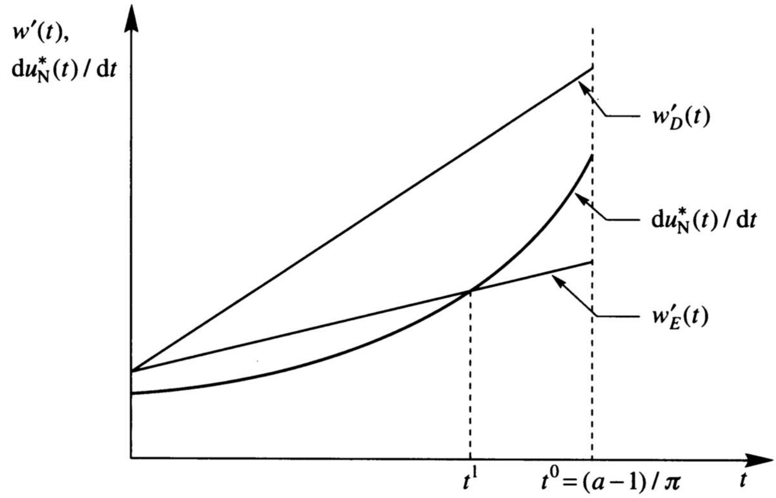

Fig. 3: Possible subgame perfect transfers when the North's preference for environmental quality is at least as strong as the South's, and $du_N^*(0)/dt < w'(0)$

in the North to discard technological aid as too expensive, when in fact the truly optimal policy is to make its best abatement technology available to the South.[16]

4 Concluding Remarks

By examining some of the circumstances under which an advanced nation can use technological aid to its strategic advantage, we have generated results that lend some theoretical support to policy recommendations about the transfer of superior pollution-control technologies to less-advanced nations. When a cooperative agreement to control a transboundary pollutant is prohibitively difficult, investing in the abatement capability of another affects future interaction in ways that are favorable to the donor nation; namely, the investment shifts a portion of the burden of noncooperative pollution control away from itself. With a similar model, Buchholz and Konrad (1994) found that countries may be motivated to adopt inferior abatement technologies for them-

16 The problem of multiple local optima disappears with constant marginal transfer costs, but in this case either no transfer is optimal or the transfer of the best technology is optimal.

selves for the same reason. But, the two strategies have very different welfare and environmental consequences. Adoption of an inferior control technology, though rational from a single country's perspective, unambiguously leads to a Pareto-inferior pollution control and worse environmental quality. In contrast, when an advanced country finds it optimal to invest in the abatement capability of another, doing so will induce Pareto-superior control and better environmental quality.

However, we have also identified a number of aspects of technological aid that should be cautionary notes for policymakers in advanced countries. In some cases, a less-advanced country may be made worse off by adopting a superior control technology. In other situations, technological aid will just be too costly; the welfare gain that the donor nation expects from improved environmental quality and being able to choose a lower level of control does not outweigh the cost of transferring a superior technology. Furthermore, in Sect. 3 we showed with an example that identifying an optimal transfer may be quite difficult. If policymakers in advanced countries do not consider benefits and costs over the full range of possible transfers, they may settle on a locally optimal transfer that is not a global optimum. Or, examining only modest investments in the abatement capabilities of another nation may lead them to discard technological aid as too costly when, in fact, a grand investment may be optimal.

There are a number of policy-relevant extensions of this paper that should be considered. For example, because we focused on a two-player game we have ignored the fact that a number of technologically advanced nations may consider policies of technological aid. Since each of the potential donor nations is made better off when one of them gives a superior technology to a less-advanced nation, each of them has an incentive to freeride on the technology transfers of the others. Furthermore, because of the freeriding incentive, the countervailing incentive to cooperate in the transfer of control technologies also exists. It seems likely that the incentives to freeride and cooperate will be important policy considerations in this context.

This work should also be extended to consider the strategic potential of technological aid when parties expect to come to a cooperative agreement to limit emissions of a global pollutant. One could consider whether an advanced country can use technological aid to stake-out a favorable negotiating position or to induce others to join an existing international environmental agreement. One might also consider how the strategic use of technological aid is likely to affect the terms of an eventual agreement, paying particular attention to the welfare and environmental consequences. Furthermore, since a number of international environmental agreements include provisions to facilitate technology transfer, researchers should begin to think seriously about how these mechanisms ought to be designed. These issues (and probably others) should be pursued in future work to provide policymakers with a more complete characterization of the potential of technological aid in international environmental relations.

Appendix 1

Our purpose is to show the following:

$$\frac{\mathrm{d}\phi_{\mathrm{N}}(x_{\mathrm{S}})}{\mathrm{d}x_{\mathrm{S}}} \in (-1,0), \quad \frac{\partial \phi_{\mathrm{S}}(x_{\mathrm{N}},t)}{\partial x_{\mathrm{N}}} \in (-1,0), \quad \text{and} \quad \frac{\partial \phi_{\mathrm{S}}(x_{\mathrm{N}},t)}{\partial t} > 0 \, .$$

Consider the South's optimization problem $\max_{x_{\mathrm{S}}} u_{\mathrm{S}}(x_{\mathrm{N}} + x_{\mathrm{S}}, m_{\mathrm{S}} - c_{\mathrm{S}}(x_{\mathrm{S}}, t))$, and the first-order condition

$$\frac{\partial u_{\mathrm{S}}}{\partial x_{\mathrm{S}}} = \frac{\partial u_{\mathrm{S}}}{\partial X} - \frac{\partial u_{\mathrm{S}}}{\partial y_{\mathrm{S}}}\frac{\partial c_{\mathrm{S}}}{\partial x_{\mathrm{S}}} = 0 \, ,$$

where $X = x_{\mathrm{N}} + x_{\mathrm{S}}$. This first-order condition implicitly defines the best-response function $x_{\mathrm{S}} = \phi_{\mathrm{S}}(x_{\mathrm{N}}, t)$. Then,

$$\frac{\partial \phi_{\mathrm{S}}}{\partial x_{\mathrm{N}}} = -\frac{\partial^2 u_{\mathrm{S}}/\partial x_{\mathrm{N}}\partial x_{\mathrm{S}}}{\partial^2 u_{\mathrm{S}}/\partial x_{\mathrm{S}}^2} \, .$$

Now,

$$\frac{\partial^2 u_{\mathrm{S}}}{\partial x_{\mathrm{S}}\partial x_{\mathrm{N}}} = \left(\frac{\partial^2 u_{\mathrm{S}}}{\partial X^2} - \frac{\partial^2 u_{\mathrm{S}}}{\partial X \partial y_{\mathrm{S}}}\frac{\partial c_{\mathrm{S}}}{\partial x_{\mathrm{S}}}\right) - \left(\frac{\partial^2 u_{\mathrm{S}}}{\partial X \partial y_{\mathrm{S}}}\frac{\partial c_{\mathrm{S}}}{\partial x_{\mathrm{S}}}\right)$$

and

$$\frac{\partial^2 u_{\mathrm{S}}}{\partial x_{\mathrm{S}}^2} = \left(\frac{\partial^2 u_{\mathrm{S}}}{\partial X^2} - \frac{\partial^2 u_{\mathrm{S}}}{\partial X \partial y_{\mathrm{S}}}\frac{\partial c_{\mathrm{S}}}{\partial x_{\mathrm{S}}}\right) - \left(\frac{\partial^2 u_{\mathrm{S}}}{\partial X \partial y_{\mathrm{S}}} - \frac{\partial^2 u_{\mathrm{S}}}{\partial y_{\mathrm{S}}^2}\frac{\partial c_{\mathrm{S}}}{\partial x_{\mathrm{S}}}\right)\frac{\partial c_{\mathrm{S}}}{\partial x_{\mathrm{S}}} - \left(\frac{\partial^2 c_{\mathrm{S}}}{\partial x_{\mathrm{S}}^2}\frac{\partial u_{\mathrm{S}}}{\partial y_{\mathrm{S}}}\right) .$$

The assumptions we made in the text about the utility and abatement-cost functions include

$$\begin{aligned}&\frac{\partial u_{\mathrm{S}}}{\partial X} > 0, \quad \frac{\partial^2 u_{\mathrm{S}}}{\partial X^2} < 0, \quad \frac{\partial u_{\mathrm{S}}}{\partial y_{\mathrm{S}}} > 0, \quad \frac{\partial^2 u_{\mathrm{S}}}{\partial y_{\mathrm{S}}^2} \leq 0,\\ &\frac{\partial^2 u_{\mathrm{S}}}{\partial X \partial y_{\mathrm{S}}} \geq 0, \quad \frac{\partial c_{\mathrm{S}}}{\partial x_{\mathrm{S}}} > 0, \quad \text{and} \quad \frac{\partial^2 c_{\mathrm{S}}}{\partial x_{\mathrm{S}}^2} > 0 .\end{aligned} \tag{A1}$$

Using (A1) we have

$$\frac{\partial^2 u_{\mathrm{S}}}{\partial x_{\mathrm{S}} \partial x_{\mathrm{N}}} < 0, \quad \frac{\partial^2 u_{\mathrm{S}}}{\partial x_{\mathrm{S}}^2} < 0, \quad \text{and} \quad \left|\frac{\partial^2 u_{\mathrm{S}}}{\partial x_{\mathrm{S}}^2}\right| > \left|\frac{\partial^2 u_{\mathrm{S}}}{\partial x_{\mathrm{S}} \partial x_{\mathrm{N}}}\right| ,$$

which imply $\partial \phi_{\mathrm{S}}/\partial x_{\mathrm{N}} \in (-1, 0)$. [Note that the assumptions of (A1) are sufficient to obtain this result but are not necessary.] In a similar fashion, $\mathrm{d}\phi_{\mathrm{N}}/\mathrm{d}x_{\mathrm{S}} \in (-1, 0)$ is easily obtained. Lastly,

$$\frac{\partial \phi_{\mathrm{S}}}{\partial t} = -\frac{\partial^2 u_{\mathrm{S}}/\partial x_{\mathrm{S}} \partial t}{\partial^2 u_{\mathrm{S}}/\partial x_{\mathrm{S}}^2} ,$$

where

$$\frac{\partial^2 u_{\mathrm{S}}}{\partial x_{\mathrm{S}} \partial t} = -\left(\frac{\partial^2 u_{\mathrm{S}}}{\partial X \partial y_{\mathrm{S}}} \frac{\partial c_{\mathrm{S}}}{\partial t}\right) + \left(\frac{\partial^2 u_{\mathrm{S}}}{\partial y_{\mathrm{S}}^2} \frac{\partial c_{\mathrm{S}}}{\partial x_{\mathrm{S}}} \frac{\partial c_{\mathrm{S}}}{\partial t}\right) - \left(\frac{\partial^2 c_{\mathrm{S}}}{\partial x_{\mathrm{S}} \partial t} \frac{\partial u_{\mathrm{S}}}{\partial y_{\mathrm{S}}}\right) .$$

In addition to the assumptions listed in (A1), we also have $\partial c_{\mathrm{S}}/\partial t < 0$ and $\partial^2 c_{\mathrm{S}}/\partial x_{\mathrm{S}} \partial t < 0$. Then, $\partial^2 u_{\mathrm{S}}/\partial x_{\mathrm{S}} \partial t > 0$ which with $\partial^2 u_{\mathrm{S}}/\partial x_{\mathrm{S}}^2 < 0$ implies $\partial \phi_{\mathrm{S}}/\partial t > 0$.

Appendix 2

Given some transfer from the first-stage that the South adopts, and assuming an interior second-stage equilibrium, the first-order conditions to the optimization problems given by (8) in the text are

$$\beta_{\mathrm{N}} - x_{\mathrm{N}} - x_{\mathrm{S}} - x_{\mathrm{N}} = 0 \tag{A2.1}$$

and

$$\beta_{\mathrm{S}} - \eta(x_{\mathrm{N}} + x_{\mathrm{S}}) - (a - \pi t)x_{\mathrm{S}} = 0 . \tag{A2.2}$$

Solving the first-order conditions yields the equilibrium abatement choices given by (9) in the text:

$$x_{\mathrm{N}}^*(t) = \frac{\beta_{\mathrm{N}}(\eta + (a - \pi t)) - \beta_{\mathrm{S}}}{\eta + 2(a - \pi t)}, \quad \text{and} \quad x_{\mathrm{S}}^*(t) = \frac{2\beta_{\mathrm{S}} - \eta\beta_{\mathrm{N}}}{\eta + 2(a - \pi t)} . \tag{A2.3}$$

The marginal effects on abatement of the technology transferred in the first stage of the game are

$$\frac{\mathrm{d}x_{\mathrm{N}}^*(t)}{\mathrm{d}t} = \frac{-\pi(2\beta_{\mathrm{S}} - \eta\beta_{\mathrm{N}})}{[\eta + 2(a - \pi t)]^2} < 0 , \tag{A2.4}$$

$$\frac{\mathrm{d}x_{\mathrm{S}}^*(t)}{\mathrm{d}t} = \frac{2\pi(2\beta_{\mathrm{S}} - \eta\beta_{\mathrm{N}})}{[\eta + 2(a - \pi t)]^2} > 0 , \tag{A2.5}$$

and

$$\frac{\mathrm{d}[x_{\mathrm{N}}^*(t) + x_{\mathrm{S}}^*(t)]}{\mathrm{d}t} = \frac{\pi(2\beta_{\mathrm{S}} - \eta\beta_{\mathrm{N}})}{[\eta + 2(a - \pi t)]^2} > 0 . \tag{A2.6}$$

To show that the South's payoff is increasing in superior technologies, consider

$$u_{\mathrm{S}}^*(t) = \beta_{\mathrm{S}}[x_{\mathrm{N}}^*(t) + x_{\mathrm{S}}^*(t)] - \frac{\eta}{2}[x_{\mathrm{N}}^*(t) + x_{\mathrm{S}}^*(t)]^2 - \frac{a - \pi t}{2} x_{\mathrm{S}}^*(t)^2 .$$

Differentiating, using the first-order condition (A2.2), and substituting for $x_{\mathrm{S}}^*(t)$ from (A2.3) and $\mathrm{d}x_{\mathrm{N}}^*(t)/\mathrm{d}t$ from (A2.4) yields

$$\frac{\mathrm{d}u_{\mathrm{S}}^*(t)}{\mathrm{d}t} = \frac{\pi\eta(2\beta_{\mathrm{S}} - \eta\beta_{\mathrm{N}})^2}{2[\eta + 2(a - \pi t)]^3} > 0 .$$

Now consider the North's second-stage equilibrium payoff (absent the transfer cost):

$$u_{\mathrm{N}}^*(t) = \beta_{\mathrm{N}}[x_{\mathrm{N}}^*(t) + x_{\mathrm{S}}^*(t)] - \tfrac{1}{2}[x_{\mathrm{N}}^*(t) + x_{\mathrm{S}}^*(t)]^2 - \tfrac{1}{2}x_{\mathrm{N}}^*(t)^2 . \tag{A2.7}$$

To confirm that $u_{\mathrm{N}}^*(t)$ is increasing in t, differentiate (A2.7) and use the first-order condition (A2.1) to obtain

$$\frac{\mathrm{d}u_{\mathrm{N}}^*(t)}{\mathrm{d}t} = \frac{\mathrm{d}x_{\mathrm{S}}^*(t)}{\mathrm{d}t} x_{\mathrm{N}}^*(t) > 0 . \tag{A2.8}$$

The inequality follows because $dx_S^*(t)/dt > 0$ [see (A2.5)]. To show that $u_N^*(t)$ and $du_N^*(t)/dt$ are both strictly convex, from (A2.8) obtain

$$\frac{d^2u_N^*(t)}{dt^2} = \frac{d^2x_S^*(t)}{dt^2}x_N^*(t) + \frac{dx_N^*(t)}{dt}\frac{dx_S^*(t)}{dt} \ .$$

Use (A2.3), (A2.4), and (A2.5) to obtain

$$\frac{d^2u_N^*(t)}{dt^2} = \frac{2\pi^2(2\beta_S - \eta\beta_N)}{[\eta + 2(a - \pi t)]^4}\{5\beta_N\eta + 4\beta_N(a - \pi t) - 6\beta_S\} \ .$$

The first term on the right-hand side is positive, so concavity or convexity of $u_N^*(t)$ depends on the sign of $G(t) = \{5\beta_N\eta + 4\beta_N(a - \pi t) - 6\beta_S\}$. That is, $\text{sign}[d^2u_N^*(t)/dt^2] = \text{sign}\, G(t)$. Furthermore, it is easy to show that the sign of $d^3u_N^*(t)/dt^3$ is the same as the sign of $H(t) = \{3\beta_N\eta + 2\beta_N(a - \pi t) - 4\beta_S\}$. Now, since $G(t)$ and $H(t)$ are both decreasing in t and t is at most $(a - 1)/\pi$,

$$G(t) \geq \{4\beta_N(\eta + 1) + \beta_N\eta - 6\beta_S\} \ , \tag{A2.9}$$

and

$$H(t) \geq \{2\beta_N(\eta + 1) + \beta_N\eta - 4\beta_S\} \ , \tag{A2.10}$$

for all $t \in [0, (a - 1)/\pi]$. Assuming as we do that the North's demand for environmental quality is at least as strong as the South's, so that $\beta_N \geq \beta_S$ and $\eta \geq 1$, the right-hand sides of (A2.9) and (A2.10) are strictly positive, and hence, $G(t)$ and $H(t)$ are both strictly positive for all $t \in [0, (a-1)/\pi]$. Thus, when the North's demand for environmental quality is at least as strong as the South's, $u_N^*(t)$ and $du_N^*(t)/dt$ are both strictly convex.

References

Barrett, S. (1994): "Self Enforcing International Environmental Agreements." *Oxford Economic Papers* 46: 878–894.

Baumol, W. J., and Oates, W. E. (1988): *The Theory of Environmental Policy.* Cambridge: Cambridge University Press.

Benedick, R. E. (1991): *Ozone Diplomacy: New Directions in Safeguarding the Planet.* Cambridge, MA: Harvard University Press.

Bergstrom, T., Blume, L., and Varian, H. (1986): "On the Private Provision of Public Goods." *Journal of Public Economics* 29: 25–49.

Black, J., Levi, M. D., and de Meza, D. (1993): "Creating a Good Atmosphere: Minimum Participation for Tackling the 'Greenhouse Effect'." *Economica* 60: 281–293.

Buchholz, W., and Konrad, K. (1994): "Global Environmental Problems and the Strategic Choice of Technology." *Journal of Economics / Zeitschrift für Nationalökonomie* 60: 299–321.

—— (1995): "Strategic Transfers and Private Provision of Public Goods." *Journal of Public Economics* 57: 489–505.

Carraro, C., and Siniscalco, D. (1993): "Strategies for the International Protection of the Environment." *Journal of Public Economics* 52: 309–328.

Copeland, B. (1990): "Strategic Enhancement and Destruction of Fisheries and the Environment in the Presence of International Externalities." *Journal of Environmental Economics and Management* 19: 212–226.

Coppel, J. (1994): "Implementing a Global Abatement Policy: The Role of Transfers." In *The Economics of Climate Change*. Paris: Organisation for Economic Cooperation and Development.

Cornes, R., and Sandler, T. (1986): *The Theory of Externalities, Public Goods and Club Goods*. Cambridge: Cambridge University Press.

De Canio, S., and Lee, K. N. (1991): "Doing Well by Doing Good: Technology Transfer to Protect the Ozone." *Policy Studies Journal* 19: 140–151.

Dixit, A. (1980): "The Role of Investment in Entry Deterrence." *Economic Journal* 90: 95–106.

French, H. (1992): "Strengthening Global Environmental Governance." In *State of the World 1992*, edited by L. Brown. New York: W. W. Norton.

Fudenberg, D., and Tirole, J. (1984): "The Fat Cat Effect, the Puppy Dog Ploy, and the Lean and Hungry Look." *American Economic Review, Papers and Proceedings* 74: 361–368.

Gilbert, R. J. (1989): "Mobility Barriers and the Value of Incumbency." In *Handbook of Industrial Organization*, vol. I, edited by R. Schmalensee and R. Willig. New York: Elsevier.

Heaton, D., Sobin, R., and Repetto, R. (1991): *Transforming Technology: An Agenda for Environmentally Stable Growth in the 21st Century.* Washington DC: World Resource Institute.

Helfand, G., and Rubin, J. (1994): "Spreading versus Concentrating Damages: Environmental Policies in the Presence of Nonconvexities." *Journal of Environmental Economics and Management* 27: 84–91.

Hoel, M. (1991): "Global Environmental Problems: the Effects of Unilateral Actions Taken by One Country." *Journal of Environmental Economics and Management* 20: 55–70.

Konrad, K. (1994): "The Strategic Advantage of Being Poor: Private and Public Provision of Public Goods." *Economica* 61: 79–92.

Levy, M., Keohane, R., and Haas, P. (1993): "Improving the Effectiveness of International Environmental Institutions." In *Institutions for the Earth*, edited by P. Haas, R. Keohane, and M. Levy. Cambridge, MA: MIT Press.

Maler, K.-G. (1991): "International Environmental Problems." In *Economic Policy Towards the Environment*, edited by D. Helm. Oxford: Blackwell.

Marjit, S. (1990): "On a Non-cooperative Theory of Technology Transfer." *Economics Letters* 33: 293–298.

von Moltke, K. (1992): "International Trade, Technology Transfer and Climate Change." In *Confronting Climate Change: Risks, Implications and Responses*, edited by I. Mintzer. Cambridge: Cambridge University Press.

Parsons, E. (1993): "Protecting the Ozone Layer." In *Institutions for the Earth*, edited by P. Haas, R. Keohane, and M. Levy. Cambridge, MA: MIT Press.

Pearce, D. (Ed.) (1991): *Blueprint 2: Greening the World Economy*. London: Earthscan Publications.

Sandler, T., and Sargent, K. (1995): "Management of Transnational Commons: Coordination, Publicness and Treaty Formation." *Land Economics* 71: 145–162.

Varian, H. (1994): "Sequential Contributions to Public Goods." *Journal of Public Economics* 53: 165–186.

Welsch, H. (1993): "An Equilibrium Framework for Global Pollution Problems." *Journal of Environmental Economics and Management* 25: S64–S79.

Address of author: John K. Stranlund, Department of Resource Economics, University of Massachusetts – Amherst, 203 Draper Hall, Amherst, MA 01003, USA.